

Reanalysis of bubble chamber measurements of



PRD 90, 112017 (2014)

C. Wilkinson¹, P. Rodrigues², with thanks to the T2K NIWG

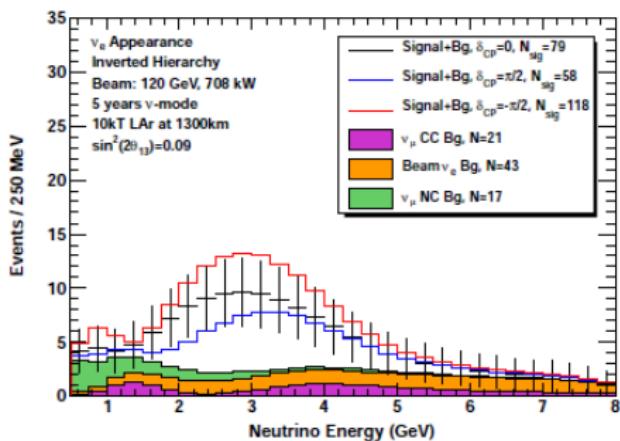
¹University of Sheffield

²University of Rochester

FNAL neutrino seminar, March 2015

Pion production contributes to signal and background processes in oscillation experiments

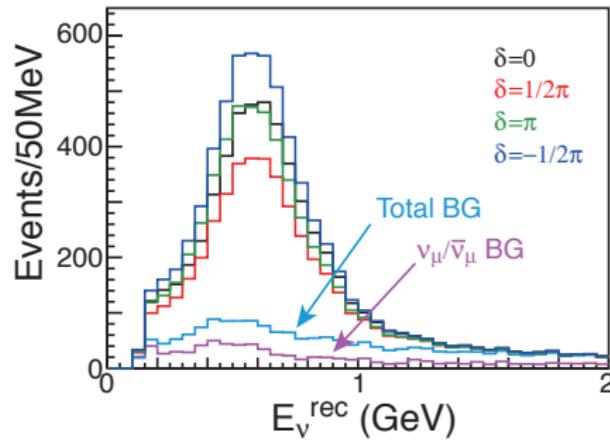
LBNE



LBNE CDR, arXiv:1307.7335

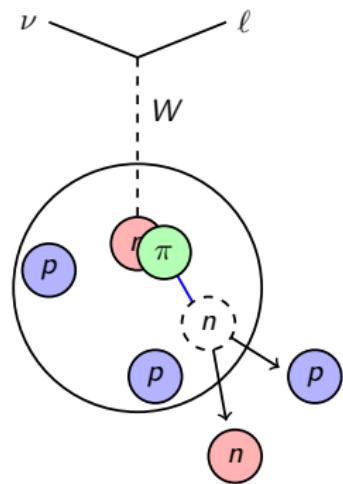
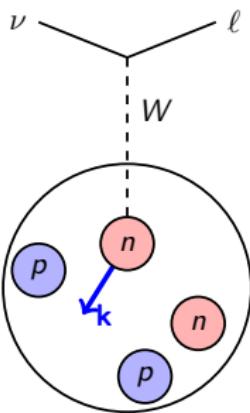
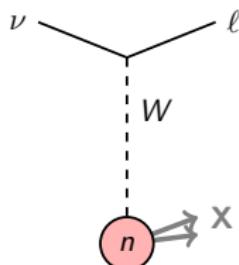
- ▶ $N(\nu_e) \propto P(\nu_\mu \rightarrow \nu_e) \times \sigma$
- ▶ Backgrounds: same resonance model for $\nu_\mu p \rightarrow \mu^- p \pi^+$ and $\nu N \rightarrow \nu N \pi^0$

HyperK

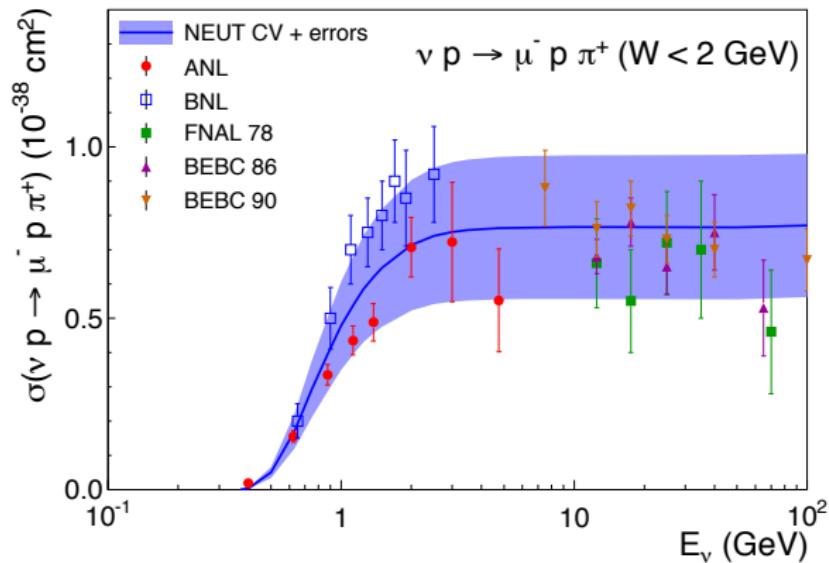


HyperK LOI, arXiv:1109.3262. NH. $\sin^2 2\theta_{13} = 0.1$

Predicting pion production on nuclei has three parts: νN , nuclear effects and FSI



The two measurements of $\nu_\mu p \rightarrow \mu^- p \pi^+$ on D₂ around 1 GeV differ by 30–40%

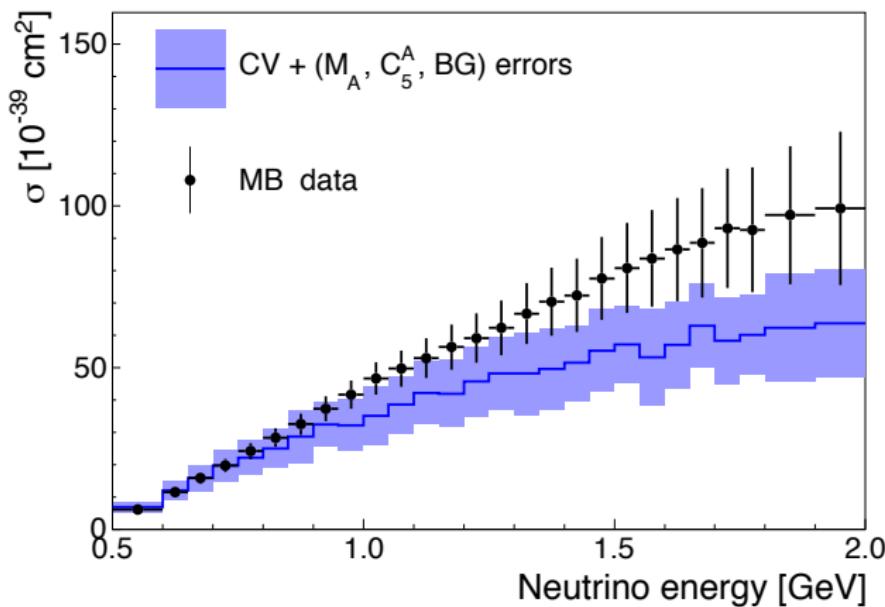


A. Bercellie and PR

- Bubble chamber measurements on D₂: ~free nucleons
- Normalization not completely constrained by theory

The discrepancy has a significant effect on predictions on nuclear targets

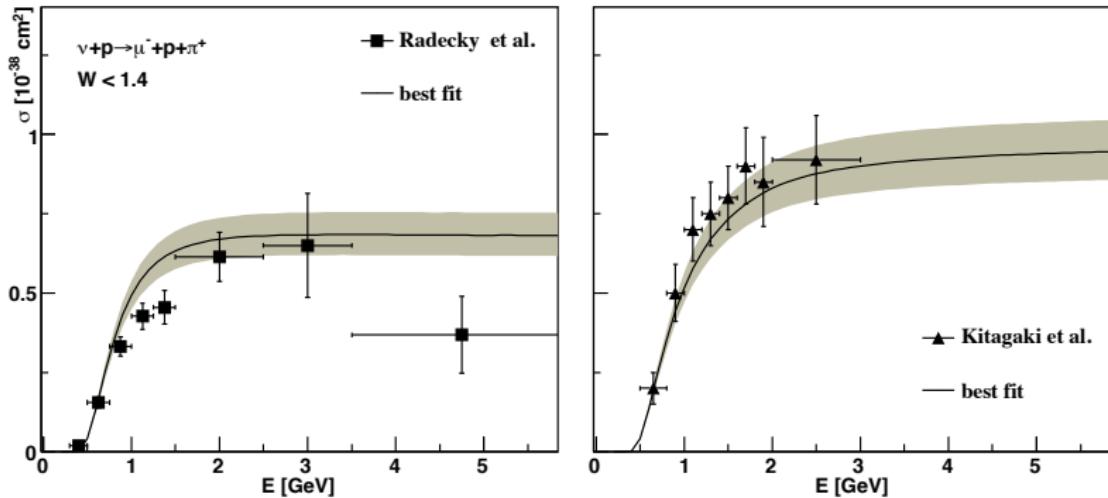
NEUT prediction for MiniBooNE CC single pion with uncertainty on nucleon form factors



A. Bercellie and PR

- ▶ Uncertainty complicates interpretation of measurements on nuclear targets

Previous work: joint fit with extra flux uncertainties



K. Graczyk et al., PRD 80, 093001 (2009)

- ▶ Fit ANL and BNL data jointly with flux uncertainties: 20% ANL; 10% BNL

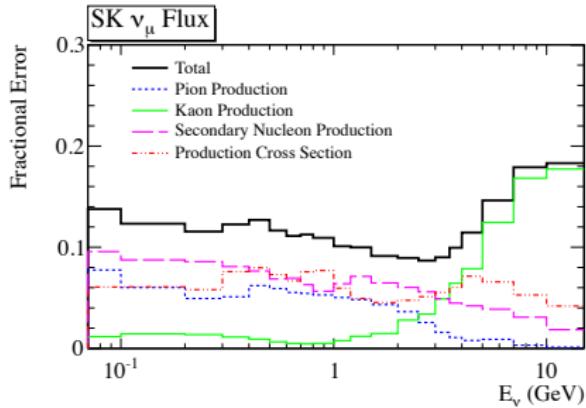
Our approach looks for consistency in ratios of event rates to other processes

- ▶ What if the only problem were normalization? (Eg, flux)

⇒ consistent

$$\sigma(\nu_\mu p \rightarrow \mu^- p \pi^+)/\sigma(\text{other}) \text{ between ANL and BNL}$$

ν flux state of the art, ca 2012

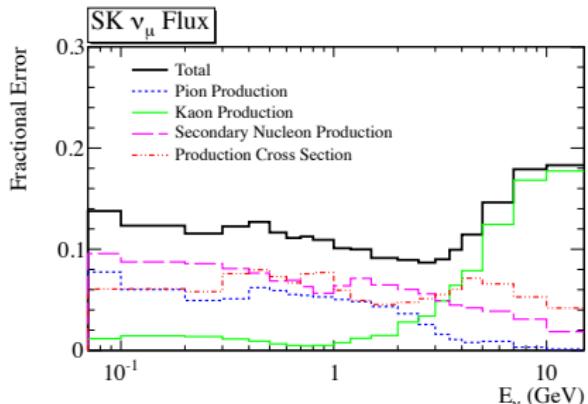


T2K, PRD 87, 012001 (2013)

Our approach looks for consistency in ratios of event rates to other processes

- ▶ What if the only problem were normalization? (Eg, flux)
 - ⇒ consistent
 $\sigma(\nu_\mu p \rightarrow \mu^- p\pi^+)/\sigma(\text{other})$ between ANL and BNL
1. Extract event counts from original papers
 2. Apply appropriate corrections (efficiency, etc)
 3. Make ratios
 $N(\nu_\mu p \rightarrow \mu^- p\pi^+)/N(\text{CCQE})$ and
 $N(\nu_\mu p \rightarrow \mu^- p\pi^+)/N(\text{CC inclusive})$

ν flux state of the art, ca 2012



T2K, PRD 87, 012001 (2013)

Extracting event counts: details and bookkeeping

- ▶ Use $\nu_\mu p \rightarrow \mu^- p\pi^+$ data with no invariant mass cut
- ▶ Digitize plots: agreement with published numbers
- ▶ Subtract events from H₂ fills
- ▶ Apply $\mathcal{O}(10 - 30\%)$ correction factors for efficiency, BG
- ▶ Repeat for CCQE, CC inclusive

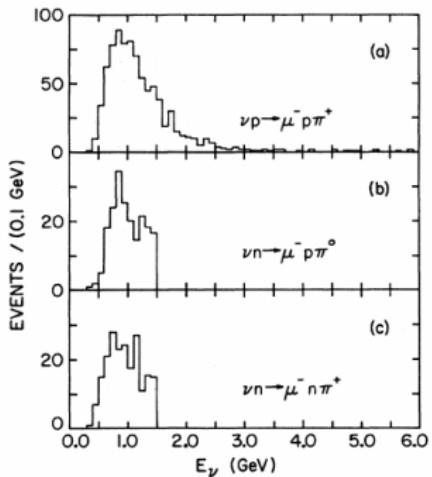
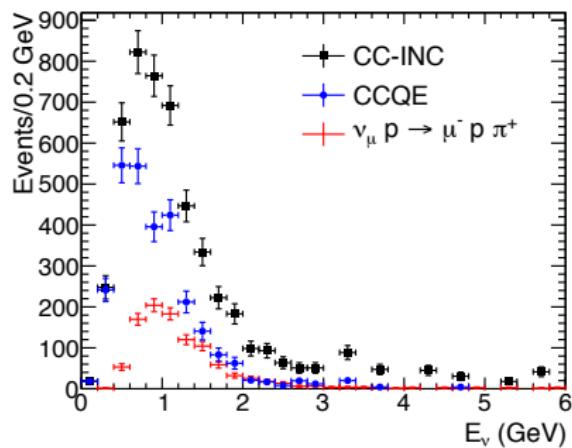


FIG. 7. The distribution of events in neutrino energy E_ν for the final states (a) $\mu^- p\pi^+$, (b) $\mu^- p\pi^0$, and (c) $\mu^- n\pi^+$. For the latter two reactions, the data are cut off at $E_\nu = 1.5$ GeV.

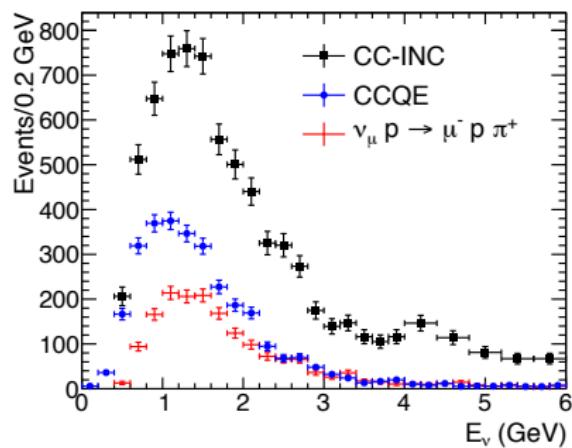
| ANL. PRD 25, 1161 (1982) | | |
|---|-----------|-----------|
| $\nu_\mu p \rightarrow \mu^- p\pi^+$ events | | |
| | Digitized | Published |
| ANL | 843 | 871 |
| BNL | 1534 | 1610 |

Extracted event counts

ANL

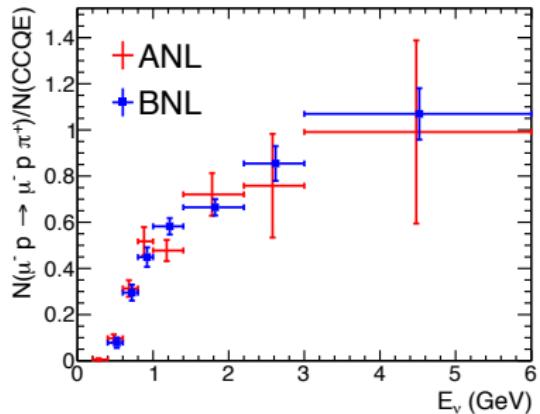


BNL

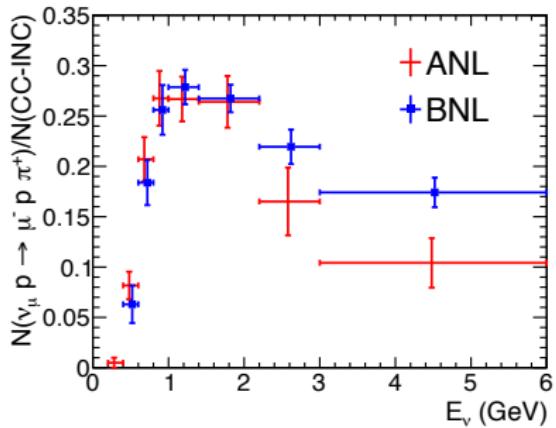


It worked! Event rate ratios are consistent between experiments

$\nu_\mu p \rightarrow \mu^- p \pi^+ / \text{CCQE}$

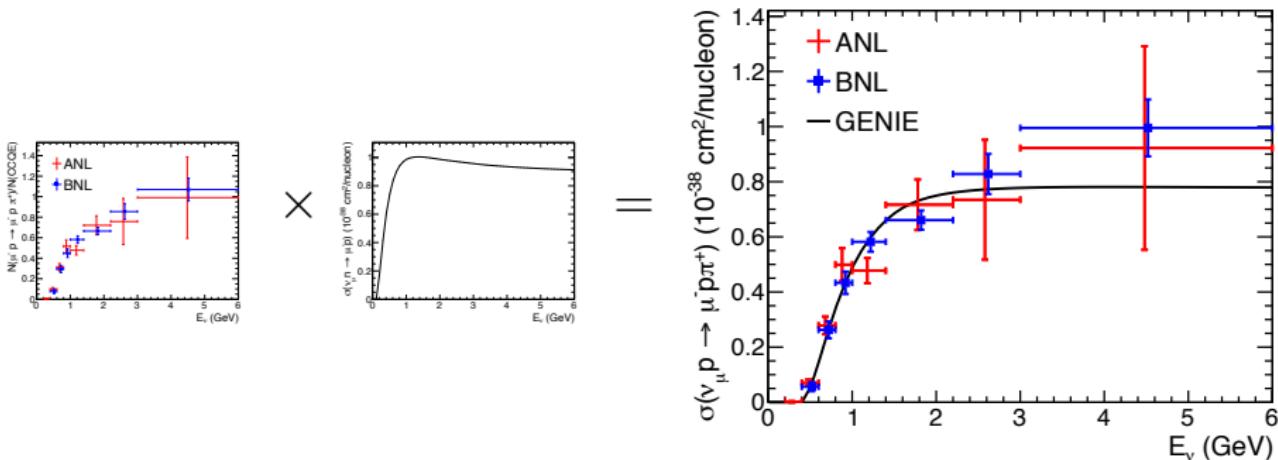


$\nu_\mu p \rightarrow \mu^- p \pi^+ / \text{CC inclusive}$



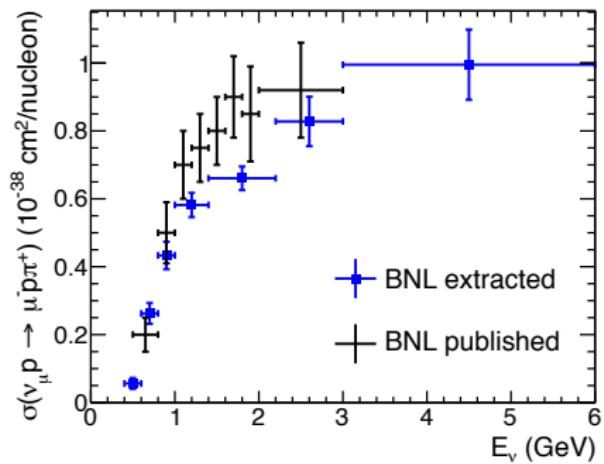
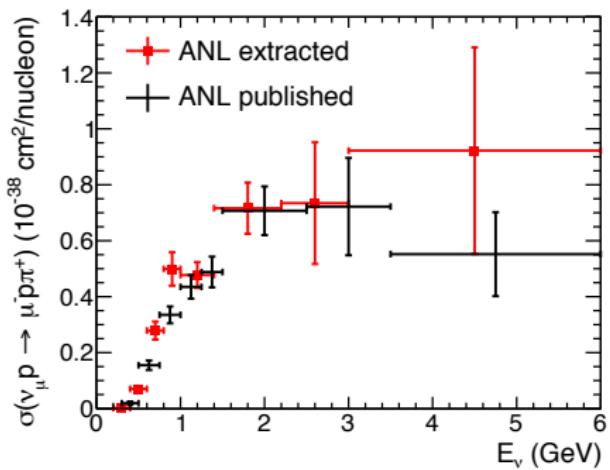
- ▶ (BNL CC inclusive H₂ contamination is harder to calculate)

Multiplying by the well-known CCQE cross section gives the
 $\nu_\mu p \rightarrow \mu^- p\pi^+$ cross section

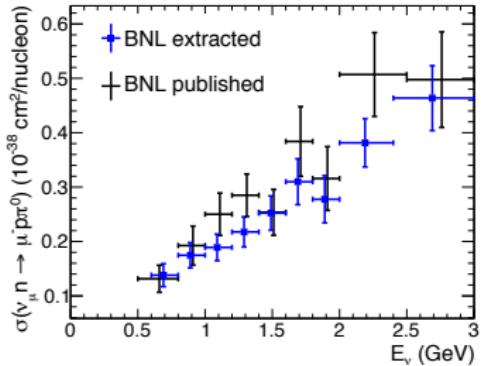
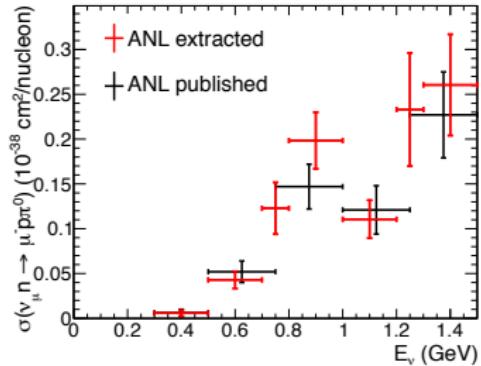
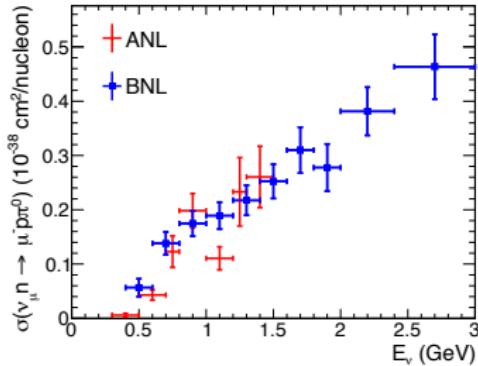


- ▶ H₂, D₂ CCQE measurements generally consistent
- ▶ Use GENIE 2.8 cross section ($M_A = 0.99$ GeV)
 - ▶ Not circular, since M_A from Q^2 shape, not normalization
- ▶ Result consistent with GENIE Δ^{++} cross section

Our cross sections pull BNL slightly more than ANL

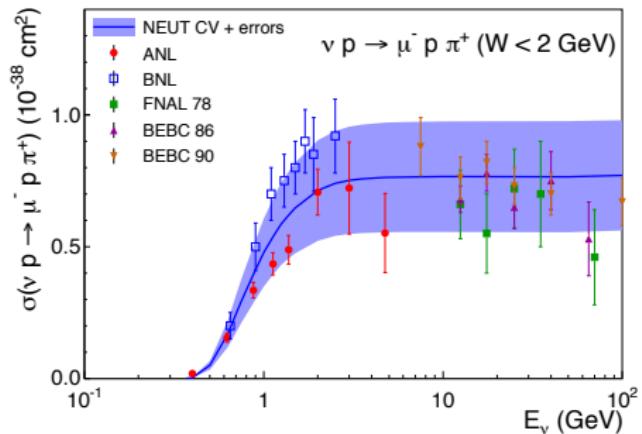


$\nu_\mu n \rightarrow \mu^- p\pi^0$ provides a consistency check

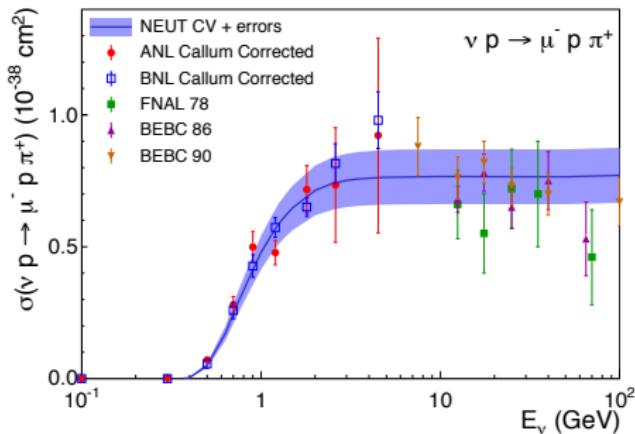


Conclusions: Updated cross section results in reduced uncertainties

Original



Reanalyzed

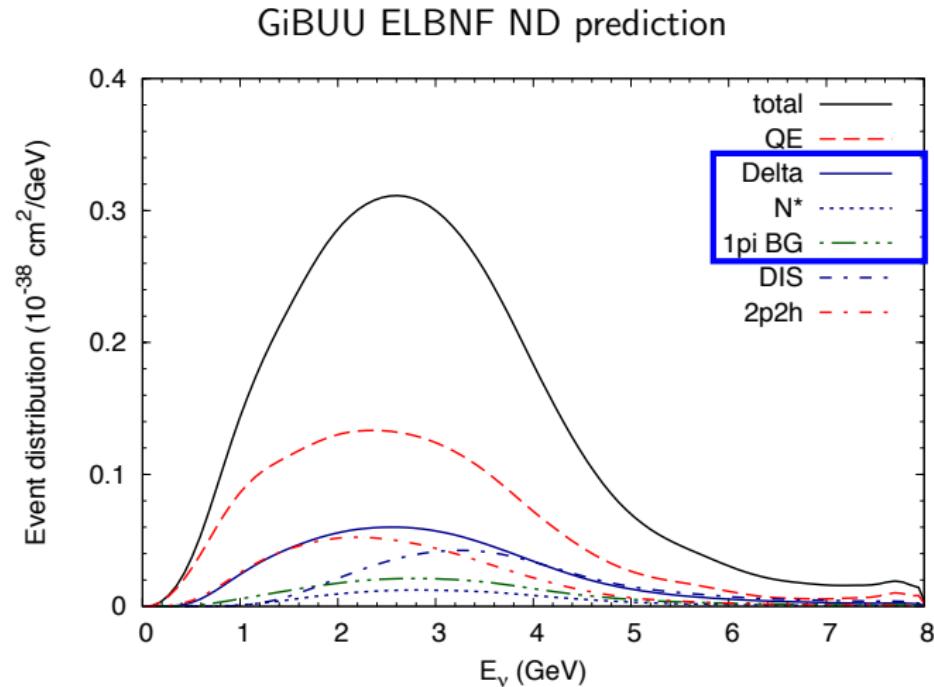


A. Bercellie and PR

- ▶ Don't need to span range of data
- ▶ Directly impacts uncertainty to be used in oscillation analyses

Backup slides

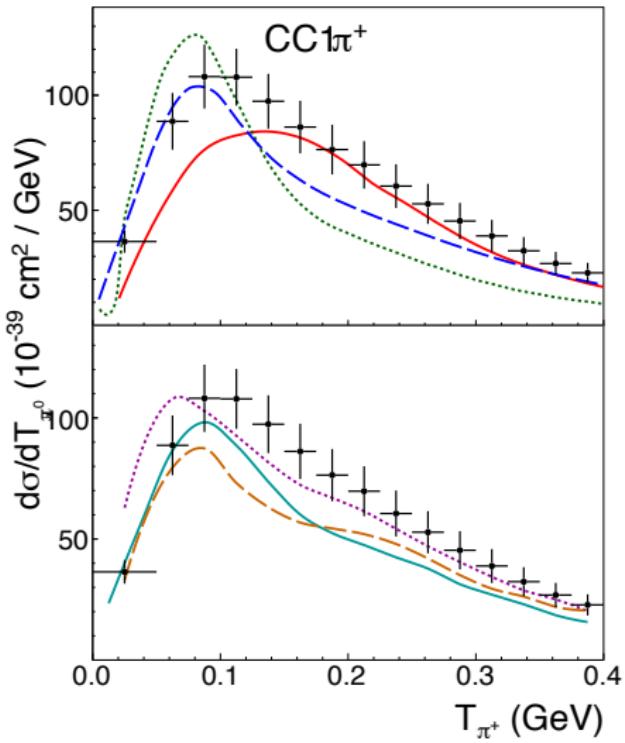
Pion production comprises a significant component of events in oscillation experiments



Pion production measurements on nuclei don't clarify the picture

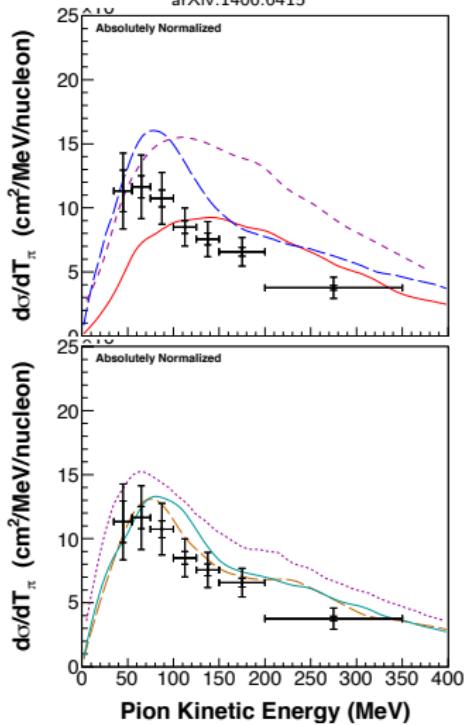
MiniBooNE

Data: PRD 83, 052007. Models: arXiv:1402.4709



MINERνA

arXiv:1406.6415



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